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Study of Timing Properties of Silicon Photomultipiers

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Abstract **A new setup has been made at Fermilab for detector timing measurements at picosecond level. The core timing resolution of the amplifiers, discriminators and TAC/ADC combination is approximately 2 picosecond. We have made a study of a single photoelectron time resolution (SPTR) measured for signals coming from silicon photomultipliers (SiPm) made by different manufacturers. The obtained SPTR is of the order of 180 picosecond with SiPms illuminated by red (635 nm) PiLas laser light. IRST SiPms show better SPTR when illuminated by the blue laser light (405 nm). Most of the data were taken with 1 Volt of the overvoltage. The SiPms time resolution is inversely proportional to the square root of the number of photoelectrons. A time-of-flight (TOF) system with few tens of picosecond time resolution, based SiPms with quartz Cherenkov radiators looks practically achievable. A simple model is proposed to explain the difference in SPTR of the IRST SiPms when illuminating by the blue and red light. The explanation of the origin of the tail in the MPPC SiPm's single photoelectron time spectra is presented. Finally, requirements for the SiPms temperature and bias voltage stability to maintain few picosecond time resolution are discussed.**

I. INTRODUCTION

Time-of-flight (TOF) measurements for subatomic particles are a very useful technique to distinguish their species. Typical resolutions for TOF have been on the order of 100 picoseconds (psec). Partly this is due to the use of scintillators for light generation, which have extended generation times. Partly this is due to the inherent limitations of large size phototubes, whose intrinsic transit time spread (TTS) is large.

The multi-pixel avalanche photodiode, also known as a Silicon Photo Multiplier, or 'SiPM', could be an option for upgrading capabilities of TOF systems. The TTS of the SiPM is about 100 psec for a single photoelectron. The blue photon detection efficiency of the devices can be as much as 65%. Thus the level of a few tens of picoseconds for TOF based on SiPM's with Cherenkov radiators looks achievable. We discuss here measurements of SiPM timing characteristics performed at the Fermi National Accelerator Laboratory (Fermilab).

II. SETUPS TO STUDY SIPM TIMING.

Two setups at the Silicon Detector Facility (SiDet) at Fermilab were created for studying SiPM timing characteristics (Fig.1). The first one contains a dark box where SiPM's under study are located. The parts of the setup are a picosecond-level pulse generator (Picosecond Pulse Lab, model 2000) used with a fast blue light emitting diode (LED) driver, and two SiPM's hooked up to VT120C Ortec fast preamps and Ortec 934 Constant Fraction Discriminators (CFD). The LED light level was changed by a rotating wheel with light attenuation filters and monitored by PIN diodes. The LED attenuated light was delivered to the SiPM's by optical fiber. The SiPM housing was mounted on a Peltier element which was used to change and stabilize the SiPM's temperature. The Peltier allowed changing the temperature in the range of 0 C to +25C with 0.5 C of accuracy. The trigger out of the picosecond pulse generator was used as the timing start signal and the CFD signal as the stop. The time difference between the start and the stop signals was measured by an Ortec 567 Time to Amplitude Converter (TAC), whose analog output was fed into an Ortec AD114 14 bit Analog to Digital Converter (ADC), located in a CAMAC crate with PC readout. This system had 50 ns of dynamic range, with a single channel resolution of 3.1 psec.

The second setup also consisted of a dark box where SiPM's were placed. The SiPM output was connected to an Ortec 9327 Ortec module (preamplifier and CFD combined in a single unit). An Ortec VT120 attenuator was used between the SiPM out and 9327 input, when needed. The SiPM's were illuminated by a PiLas laser (635 nm head with light pulse duration of 40 ps). The PiLas allows changing of the light intensity in the dynamic range 0-100%. One can monitor the laser light by a PIN diode and a small size photomultiplier. A Peltier element was also used to stabilize the SiPM's temperature, but was eventually replaced by a "Ranque-Hilsch vortex tube" to increase the temperature dynamic range and improve the temperature stability. The range of temperature is +25C to -20C inside of the dark box. Four thermocouples were installed in different places inside and outside the box to achieve better temperature control. The temperature could be changed, stabilized and monitored with about 0.1C accuracy by hardware and software managed by a PC using Lab View software. The Pilas trigger signal is used as the timing start and the 9327 NIM out signal is used as the timing stop. The

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timing measurement is the same as the first setup. A Keithley supply was used for the SiPM's as a bias supply. The unit allows keeping supplied voltages at 10 mV accuracy.

III. INITIAL TESTS OF THE SETUPS

Schematics of the initial test are shown in Figures 2 a,b,c. The start and stop signals were delivered to the TAC567 and AD114 from the same generator (fig. 2a). The so- called "electrical" time resolution was measured in this case and turned out to be 2 psec. Two peaks were obtained by introducing a 1000 psec delay into the stop signal (Fig. 3). The "warming up" time of the TAC567 plus AD114 is about 20 minutes. After half an hour the peak position is stable within +/- 1.5 psec during the next few hours at room temperature.

The next test was performed with a Hamamatsu MPPC with 1x1 mm^2 of sensitive area. This SiPM was illuminated by an intense LED. The driver pulse was used as a start signal and the SiPM as a stop signal (fig. 2b). The amount of LED light was enough to observe about 10 psec time resolution. The mean timing peak position with respect to temperature and bias voltage was taken. An 11.5 psec time shift per 1 degree F of temperature was obtained in the temperature range 59-79 F for 1 Volt overvoltage on the bias for the SiPM. A 6.2 psec time shift per 10 mV of the bias change was revealed for the same 1 Volt of overvoltage. These preliminary tests demonstrate the conditions needed to maintain the 10 ps level precision of the time resolution. We attempted to keep these conditions in future tests.

One more test was performed with a piece of plexiglass, 5 cm of thickness, installed between the LED and the SiPM. The geometry of the test was chosen in such a way that the SiPM output signal was not changed when inserting and removing the plexiglass. The result is shown in fig. 4. The mean value of the timing peak position shifted positively by 77 psec with the plexiglass and returned back to the initial position when removing the plexiglass. This time shift is in very close agreement with the time delay for light passing through 5 cm of plexiglass (the index of refraction is 1.5) instead of 5 cm of air.

IV. THE SIPM TIMING STUDY

We tested three Hamamatsu samples of 1x1 mm^2 of sensitive area: one with 100x100 μm^2 of pixel size (100 pixels on the device in total), one with 50x50 μm^2 pixel size (400 pixels) and one with 25x25 μm^2 (1600 pixels). The IRST devices were 2.8 mm diameter with 50x50 μm^2 pixel sizes (2500 pixels) and 1x1 mm^2 with 40x40 μm^2 pixel sizes (625 pixels total). The CPTA devices were 2.1x2.1 mm^2 of sensitive area with pixel size 50x50 μm^2. A single photoelectron's timing (SPT) spread distributions were taken according to the schematics in Fig. 2c. The 9327 unit accepts pulse widths up to 5 ns. A simple clipping circuit was used to shorten the SiPM's pulses (fig. 5). The efficiency of the single photon's registration was less than 10% with the chosen PiLas light intensity. The number of events with two or more photoelectrons in the timing distribution could be neglected. The SPT at a level of 180 psec was obtained for most of the SiPM's when illuminated by a 40 psec light pulse with 635 nm wavelength. One Volt of the overvoltage was applied to the SiPM's. A SPT of about 120 psec was obtained with higher overvoltage. Preliminary tests of the IRST SiPM show better single photoelectron time resolution for blue light (405 nm) than for the red one (635 nm). The Hamamatsu MPPCs reveal just the opposite, i.e. SPT for 405 nm is worse than for 635 nm. The time spread due to the Pilas light pulse could be neglected in the measurements. An inverse square root dependence of the SiPM's time resolution was observed when we increased the number of photoelectrons detected. The number of photoelectrons was estimated on the basis of the single photoelectron signal, which is perfectly defined for the SiPM's (Fig. 6). Some tails or bumps were observed for some of the single photoelectron's time distribution (Fig. 7). This effect could be referenced to optical crosstalk into some SiPM's as will be shown later. Most of the data were taken at room temperature under temperature control (73 +/-0.5 F).

V. DISCUSSION

The dependence of light absorption length on wavelength in silicon is shown in fig. 8. The electric field dependence on distance from the SiPm surface is also shown on the same picture. The picture is taken from an article of H-G Moser, MPI [1]. A more precise picture of the electric field distribution for shallow junction SiPM's produced by IRST, Italy [Claudio Piemonte report at Fermilab] is shown in Fig.9. The IRST SiPM faces the light with its n+ side. One can see that if a photon is absorbed close to the SiPM surface then the originated carriers will be holes for the IRST SiPM. Likewise, the carriers will be electrons if the photon is absorbed deep in the silicon. The absorption length is about 100 nm for 405 nm light (blue light PiLas head) and 4 μm for 635 nm (red light PiLas head). So the blue photons produce mostly holes which travel to the high electric field and develop an avalanche there eventually. The red photons produce mostly electrons traveling into the high field from the opposite direction. The mobility of holes in silicon's electric field is about 3 times less than for electrons but the hole's traveling distance is 40 times less. So the combined time spread of carriers originated by blue photons should be about one order of magnitude less than originated by red photons in the case. This simple picture does not take into consideration time jitter due to avalanche development, lateral avalanche size, etc, but only considers the initial carrier's time spread. Nevertheless, this naïve model coincides to some extent with the obtained experimental data.

A tail was observed in the single photoelectron's time spectra for some of the Hamamatsu MPPCs (Fig 7). Note, that the MPPCs face the light with their p+ side. This means the main carriers are electrons for blue light and holes for the red one, which is opposite to IRST SiPM's. These spectra were taken with 0.5 photoelectron threshold in the 9327 unit. A significant enhancement of the events in the tail was observed with 1.5 photoelectron threshold (Fig. 7). This means that the tail is mostly composed of signals with greater than one photoelectron amplitude. We will consider a simple model to explain this effect. It is already a well established fact that about one photon with more than 1eV energy is produced for every 100,000 electrons in a SiPM's avalanche [2]. The SiPM gain is about 10^6 usually, so each avalanche produces about 10 photons in average. Some of the photons, say instantly in the time scale of 100 psec, produce another charged carrier in neighboring pixels, which need time to get into the high field silicon area to create another avalanche. The signal of this avalanche is delayed with respect to the primary avalanche and overlaps with that initial one. The delay time could be of the order of hundreds to thousands of picoseconds depending on the distance between the originating avalanche and the high field area, as well as depending on the type of carriers. The triggering time of the 9327 on such a superposition of two single photoelectron signals would be a delayed output. This coincides with the obtained data as well as with the direct observation by an oscilloscope. The tail events mostly correspond to signals with two or more photoelectrons and delayed amplitude. The amount of the tail events increased with overvoltage. The observed tail in the single photoelectron time spectra is likely due to the optical crosstalk in the SiPM's. This phenomenon is well known. Some ways to suppress the crosstalk are proposed by producers [3]. We plan to order SiPM's with suppressed crosstalk and take their single photoelectron time spectra.

VII. SUMMARY OF RESULTS

A new setup for timing measurements at the picosecond level has been arranged at Fermilab. The core timing resolution of the amplifiers, discriminators and TAC/ADC combination is approximately 2 picoseconds. We have made a study of single photoelectron time resolution measured for signals coming from SiPM 's made by different manufacturers. The obtained single photoelectron time resolution (SPTR) is on the order of 180 ps with the SiPM illuminated by the red (635 nm) PiLas laser light. For the IRST SiPM the SPTR is about 10% better when illuminated by the blue laser light (405 nm), Fig. 10. Preliminary tests of the Hamamatsu MPPC show better time resolution for 635 nm than for 405 nm (for the same overvoltage), in contrast to the IRST SiPM's. Most of the data are taken with 1 Volt of overvoltage. The SPTR is better for higher overvoltage. The SiPM's time resolution is inversely proportional to the square root of the number of photoelectrons. A simple model is proposed to explain the difference in the single photoelectron time resolution when illuminating the IRST SiPM by blue and red light. The explanation of the origin of the tail in the MPPC's single photoelectron time spectra is presented. The SiPM's temperature and bias voltage stability level to maintain the few picoseconds time resolution is discussed. A time of flight (TOF) system with a few tens of picosecond time resolution, based on SiPM's with quartz Cherenkov radiators, looks achievable.

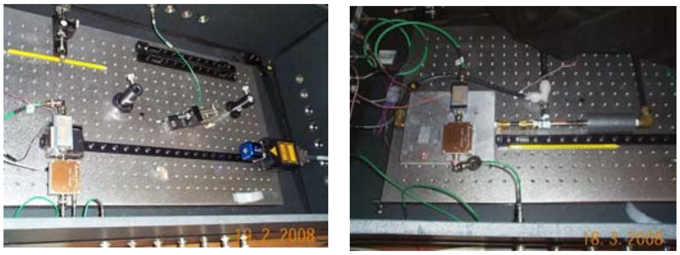


Fig. 1. Parts of the second setup: dark box with optical table inside. PiLas laser head, located on the rail.

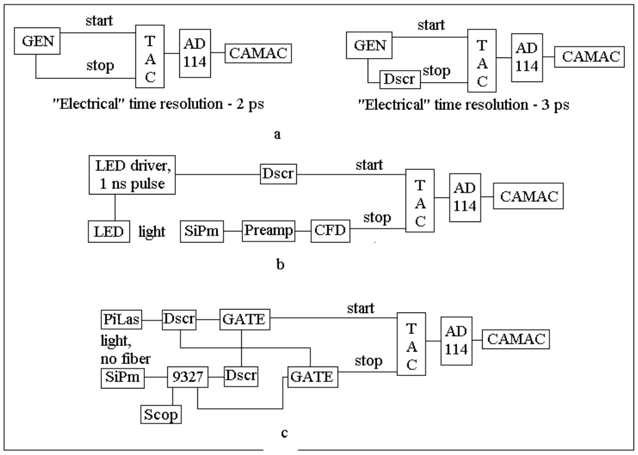
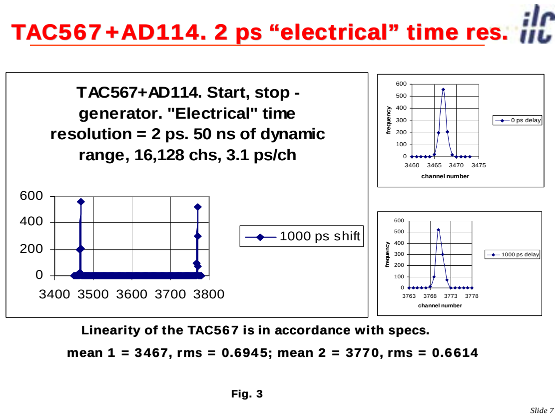


Fig. 2

Fig. 2. Schematics of the readout. GEN – generator, TAC – time – amplitude convertor, AD114 – amplitude digital convertor, LED – light emitting diode, CFD – constant fraction discriminator, PiLas – picosecond laser, SiPm – silicon photomultiplier, 9327 – 1 GHz ORTEC AMP & TIMING DISCRIMINATOR.



TAC567+AD114. 2 ps "electrical" time res.

TAC567+AD114. Start, stop - generator. "Electrical" time resolution = 2 ps. 50 ns of dynamic range, 16,128 chs, 3.1 ps/ch

Linearity of the TAC567 is in accordance with specs.

mean 1 = 3467, rms = 0.6945; mean 2 = 3770, rms = 0.6614

Fig. 3

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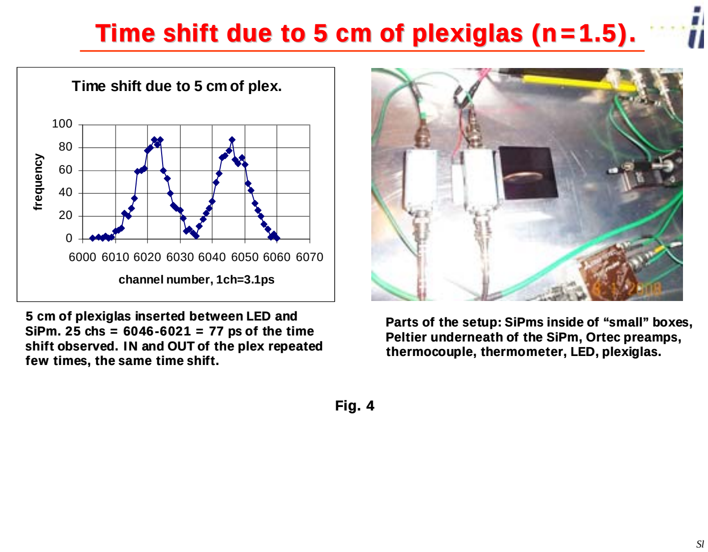
Fig. 3. "Electrical time resolution is 2 ps. Time delay with and without additional 1000 picosecond delay in "stop" channel.



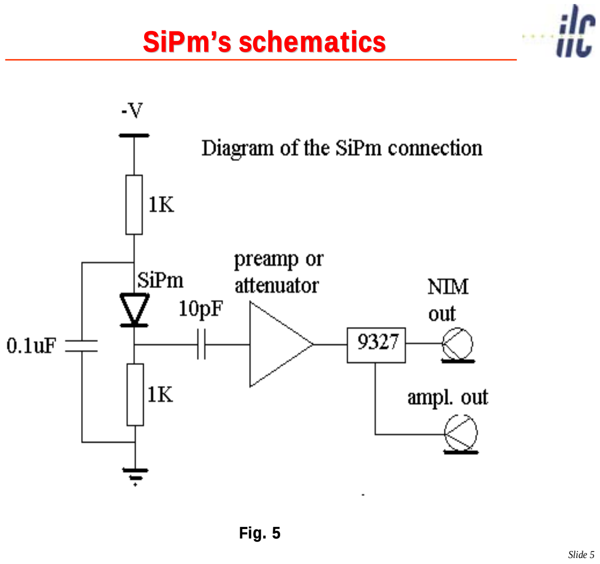
Time shift due to 5 cm of plexiglas (n=1.5).

5 cm of plexiglas inserted between LED and SiPm. 25 chs = 6046-6021 = 77 ps of the time shift observed. IN and OUT of the plex repeated few times, the same time shift.

Parts of the setup: SiPms inside of "small" boxes, Peltier underneath of the SiPm, Ortec preamps, thermocouple, thermometer, LED, plexiglas.

Fig. 4

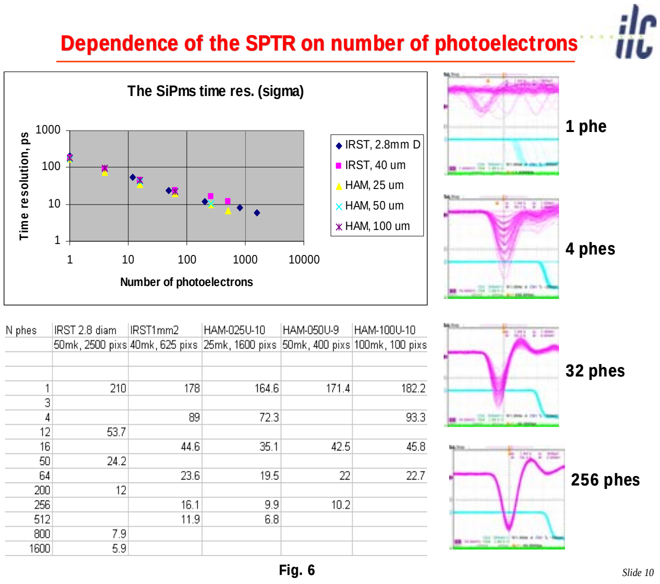
Fig. 4. Timing shift of spectra due to 5 cm of transparent plexiglass upstream of SiPm.



SiPm's schematics

Fig. 5

Fig. 5. Schematics of a SiPm signal's clipping.

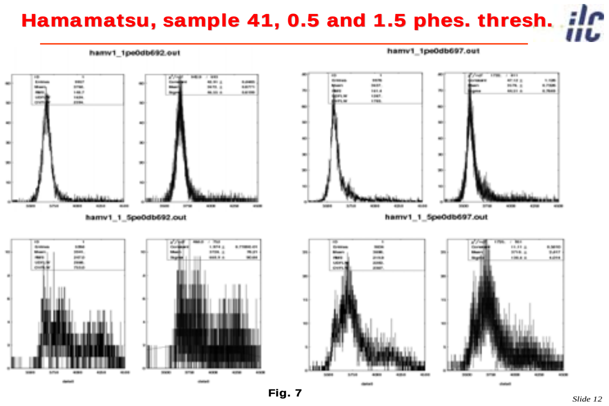


Dependence of the SPTR on number of photoelectrons

N phes	IRST 2.8 diam	IRST1mm2	HAM-025U-10	HAM-050U-9	HAM-100U-10
	50mk, 2500 pixs	40mk, 625 pixs	25mk, 1600 pixs	50mk, 400 pixs	100mk, 100 pixs
1	210	178	164.6	171.4	182.2
3					
4		89	72.3		93.3
12	53.7				
16		44.6	35.1	42.5	45.8
50	24.2				
64		23.6	19.5	22	22.7
200	12				
256		16.1	9.9	10.2	
512		11.9	6.8		
800	7.9				
1600	5.9				

Fig. 6

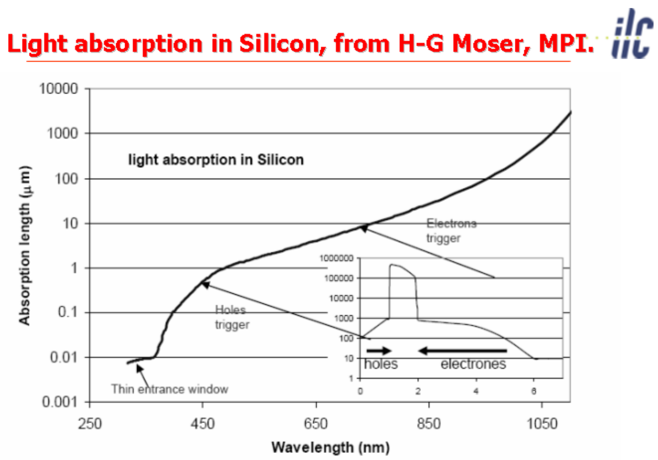
Fig. 6. Time resolution of IRST and MPPC SiPms in dependence on number of photoelectrons. Data are taken with 635 nm of the PiLas laser and 1 Volt of overvoltage.



Hamamatsu, sample 41, 0.5 and 1.5 phes. thresh.

Fig. 7

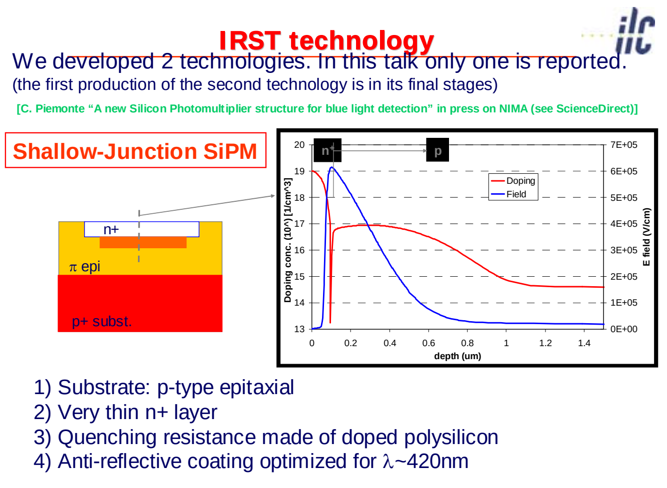
Fig. 7. Single photoelectron's timing resolution (SPTR) spectra of MPPC (Hamamatsu). Spectra with tails (on the bottom of the drawing) are obtained with 1.5 photoelectron's
threshold.



Light absorption in Silicon, from H-G Moser, MPI.

Fig. 8

Fig. 8. Absorption length in silicon in dependence of photon's wavelength. Schematics of the electric field distribution inside of a SiPm (n+ side faced to the light) in the right bottom part of the drawing.



IRST technology

We developed 2 technologies. In this talk only one is reported.

(the first production of the second technology is in its final stages)

[C. Piemonte "A new Silicon Photomultiplier structure for blue light detection" in press on NIMA (see ScienceDirect)]

Shallow-Junction SiPM

1) Substrate: p-type epitaxial
2) Very thin n+ layer
3) Quenching resistance made of doped polysilicon
4) Anti-reflective coating optimized for λ~420nm

Fig. 9

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Fig. 9. Distribution of the electric field and doping inside of IRST SiPm (top right) and the shallow-junction SiPm structure (left side of the drawing). Data presented by C. Piemonte at Fermilab.

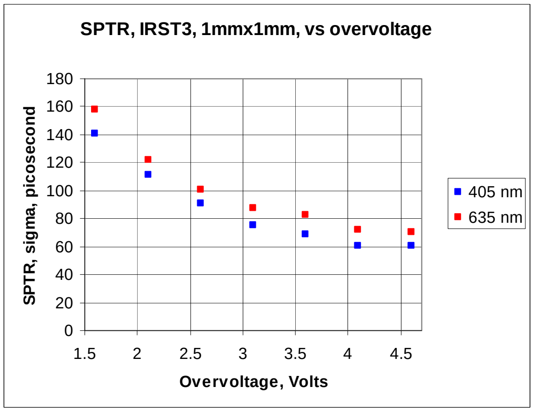

Fig. 10. SPTRs of the IRST SiPm for 635 nm and 405 nm.

Acknowledgment

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References

[1] H.G. Moser. "Silicon Photomultipliers, A New Device for Low Light Level Photon Detection". Personal communication, 2008, Fermilab.

[2] A. Lacaita, S. Cova, Spinelli, and F. Zappa."Photon-assisted avalanche spreading in reach-through photodiodes". Appl. Phys. Lett. 62 (6), 8 February 1993.

[3] C. Piemonte. "Development of Silicon Photomultiplier at IRST". Fermilab report, October 25th, 2006.